An Update Point Design for Heavy Ion Fusion

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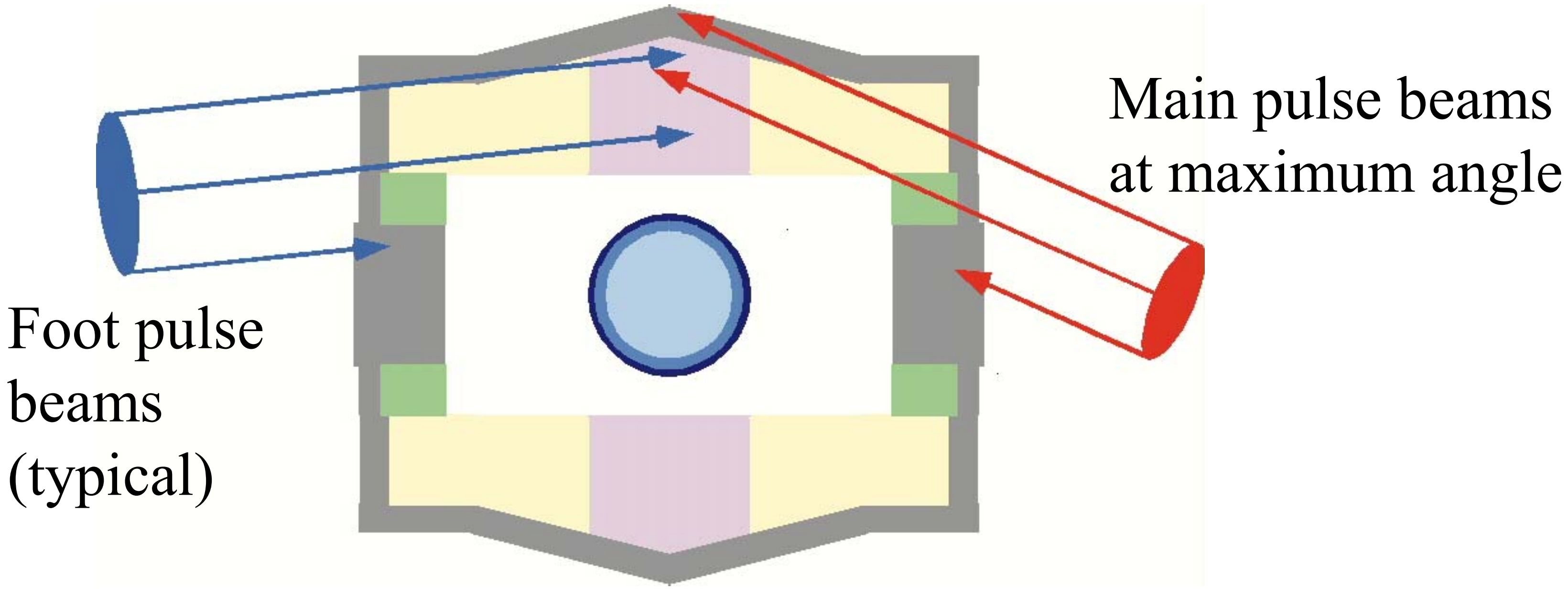
ABSTRACT

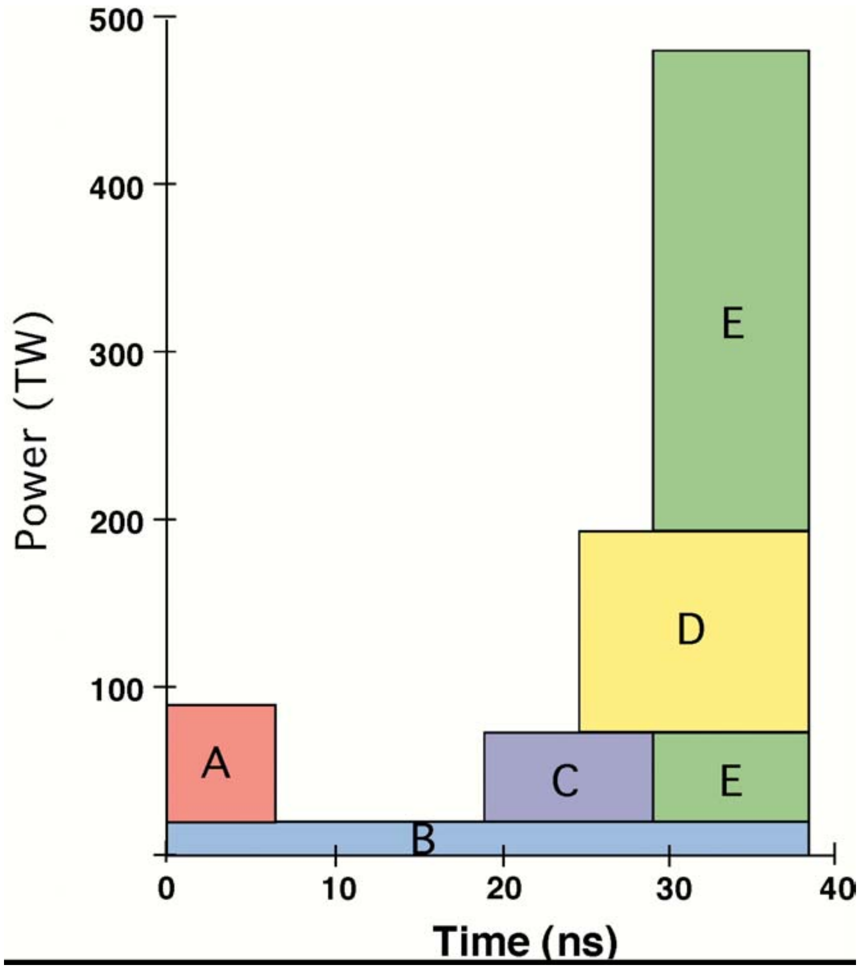
An updated, self-consistent point design for a heavy ion fusion (HIF) power plant based on an induction linac driver, indirect-drive targets, and a thick liquid wall chamber has been completed. Conservative parameters were selected to allow each design area to meet its functional requirements in a robust manner, and thus this design is referred to as the Robust Point Design. This paper provides a top-level summary of the major characteristics and design parameters for the target, driver, final focus magnet layout and shielding, chamber, beam propagation to the target, and overall power plant.

Target design is a variation of the distributed radiator target (DRT)



- This new design allows beams to come in from a larger angle, up to 24 degrees off axis.
- Yield = 400 MJ, Gain = 57 at E_{driver} = 7 MJ

A building block pulse shape is used



Beam and Pulse Shape Requirements

Block	No. of Beams	Power, TW	Pulse width, ns	Energy, MJ
A (Foot)	16	70	6.5	0.46
B (Foot)	16	20	38.3	0.77
C (Foot)	16	53	10.1	0.54
D (Main)	24	120	13.7	1.64
E (Main)	48	388	9.3	3.61

48 foot pulse beams:
$T = 3.3$ GeV, $E_F = 1.76$ MJ

72 main pulse beams:
$T = 4.0$ GeV, $E_M = 5.25$ MJ

120 total beams:
$E_D = 7.0$ MJ

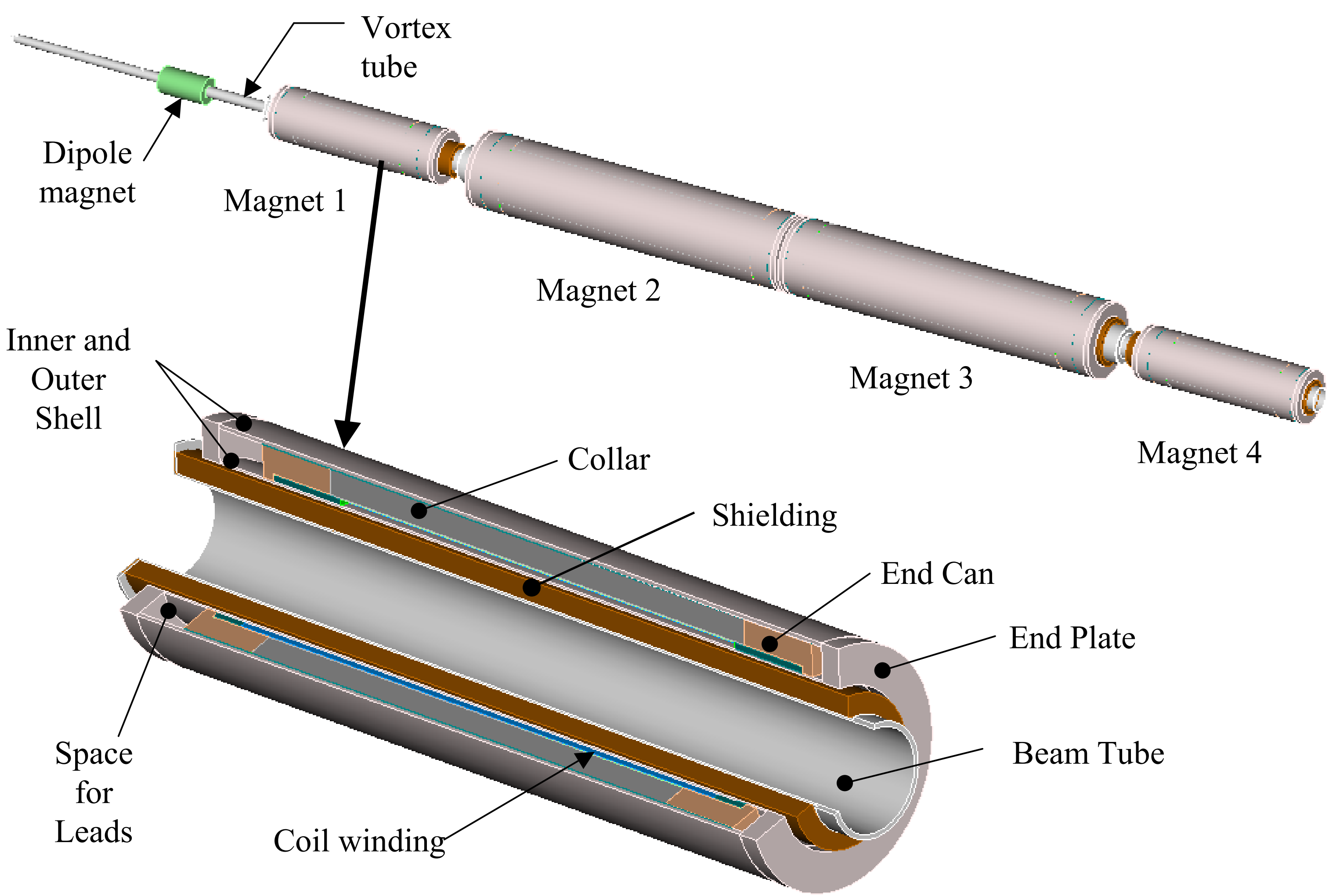
A 7 MJ induction linac driver using Bi^+ is the baseline

	Along Accelerator		
	Injector Exit	Ti = 3.3 GeV	Ti = 4.0 GeV
Ion energy, GeV	0.0016	3.3	4.0
Pulse duration, µs	30	0.2	0.2
Ion speed/light speed	0.004	0.18	0.20
Pulse length, m	36.5	10.9	12.0
Beam current, A*	0.63	94	94
Beam radius, cm*	3.8	1.9	1.9
Bore radius, cm	5.3	2.9	2.9
Field gradient, T/m	62	106	106
Core inner radius, m	1.29	0.77	0.62
Core build, m	0.48	0.47	0.47
Quad Occupancy, %	0.75	0.090	0.075
Half lattice period, m	0.30	3.83	4.43
Acc. gradient, MV/m	0.026	1.5	1.5
Dist. from injector, km	0	2.39	2.86
*For max current beams (Block E)			

Accelerator parameters at:
- Injector
- Foot pulse final energy (3.3 GeV)
- Main pulse final energy (4.0 GeV)

- **Ion = Bi^+ (A = 209 amu)**
- **Length = 2.9 km**
- **Driver efficiency = 38%**
- **Total cost = $2.8B**

Final focus configuration uses four magnets



Final focus system designed to allow for beams of variable perveance and energy

Final four magnets have same magnetic field gradient and aperture for all beam lines (with varying energy and perveance). This allows flux sharing in a magnet array (transverse) analogous to the arrays within the accelerator.

Six to eight "Matching" magnets that precede final magnets will be well separated transversely; each matching magnet gradient is tuned to the particular beam energy and perveance needed for each block of beams.

Maximum allowed field at aperture is 4 T (with maximum allowed field within magnet of 7T).

Final angle of high perveance beams (Blocks A and E) held at 10 mrad. Lower perveance beams have lower final focusing angles associated with lower emittance growth predicted in chamber.

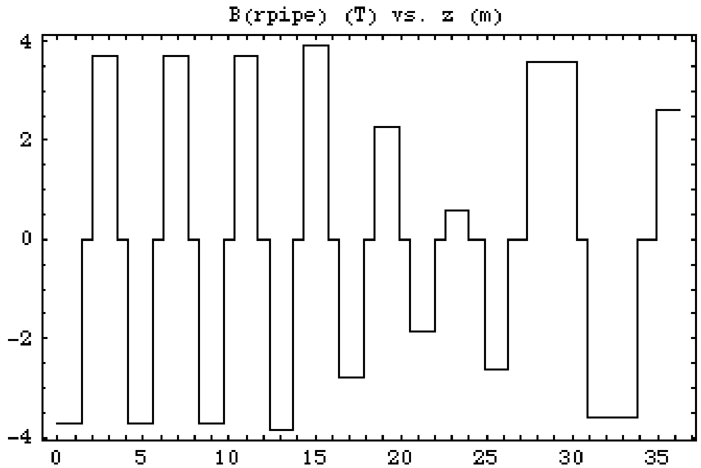
Key design parameters of final magnets

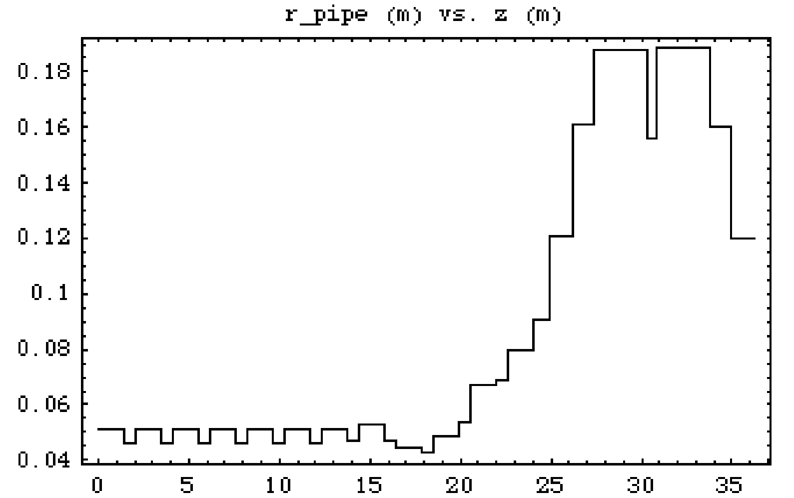
Quad*	Field gradient (T/m)	Field at pipe radius (T)	Beam pipe radius (cm)	Magnet length (m)
1st	21.8	2.61	12.0	1.33
2nd	-19.1	-3.60	18.9	3.00
3rd	19.1	3.74	19.6	3.00
4th	-21.8	-2.99	13.7	1.33
* 1st magnet is closest to chamber				

Field and pipe radii for final four magnets for foot and main pulses

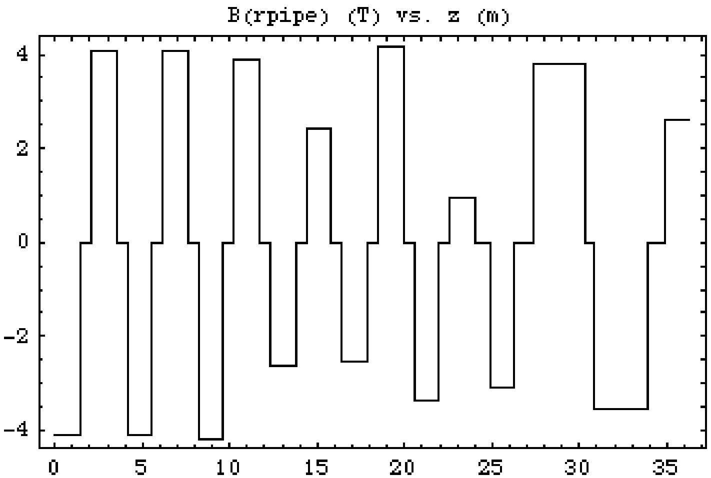
Only matching quads are different

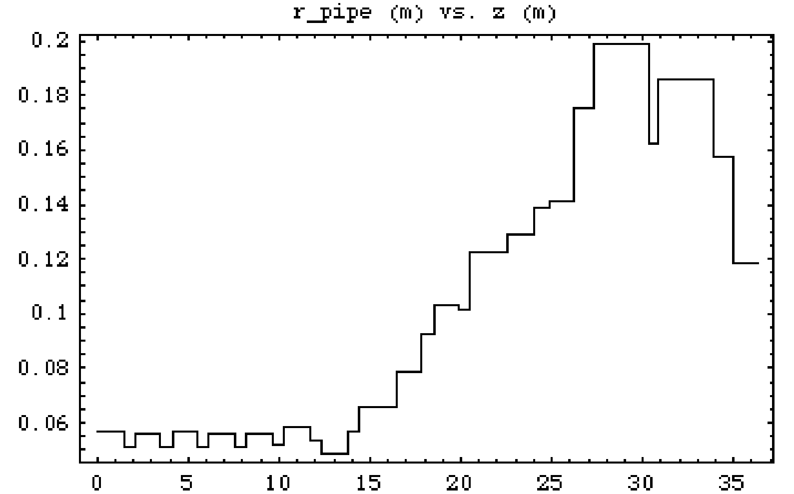
Foot



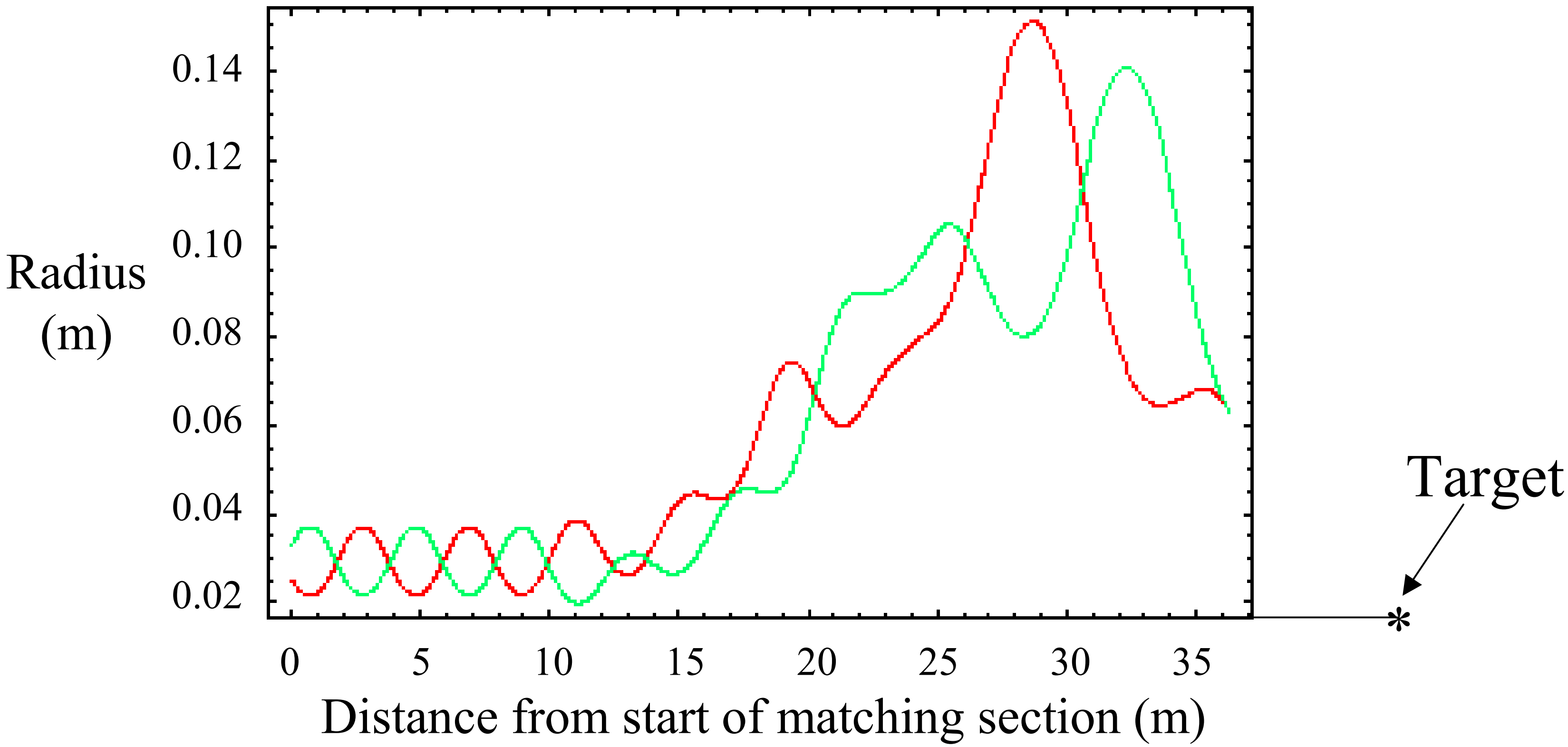


Main





Beam envelop in final focus region

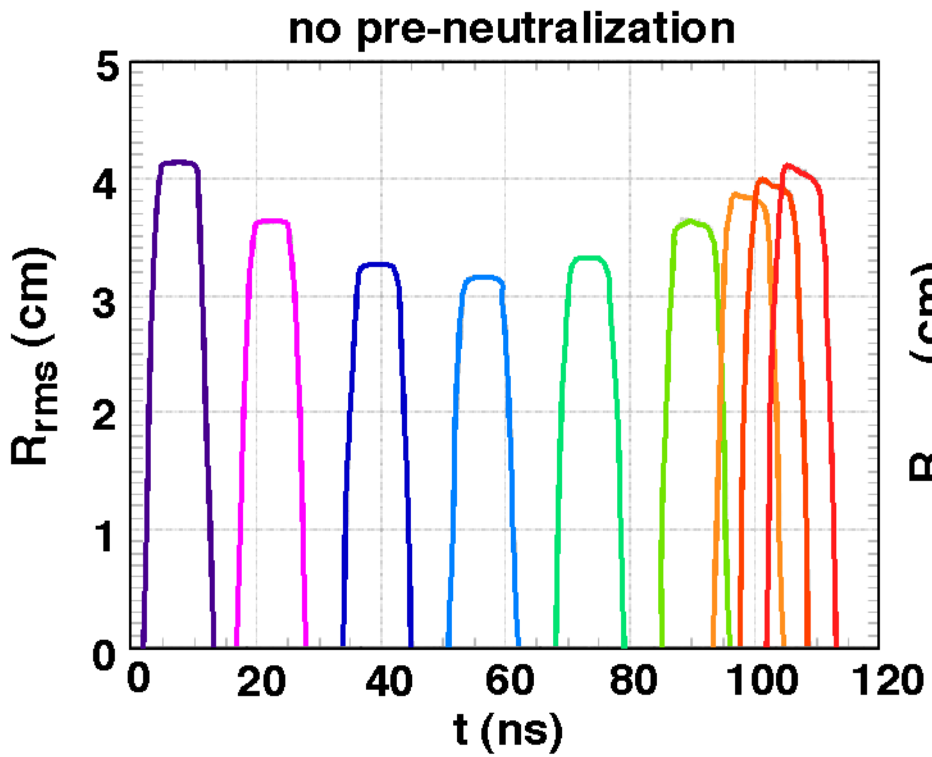


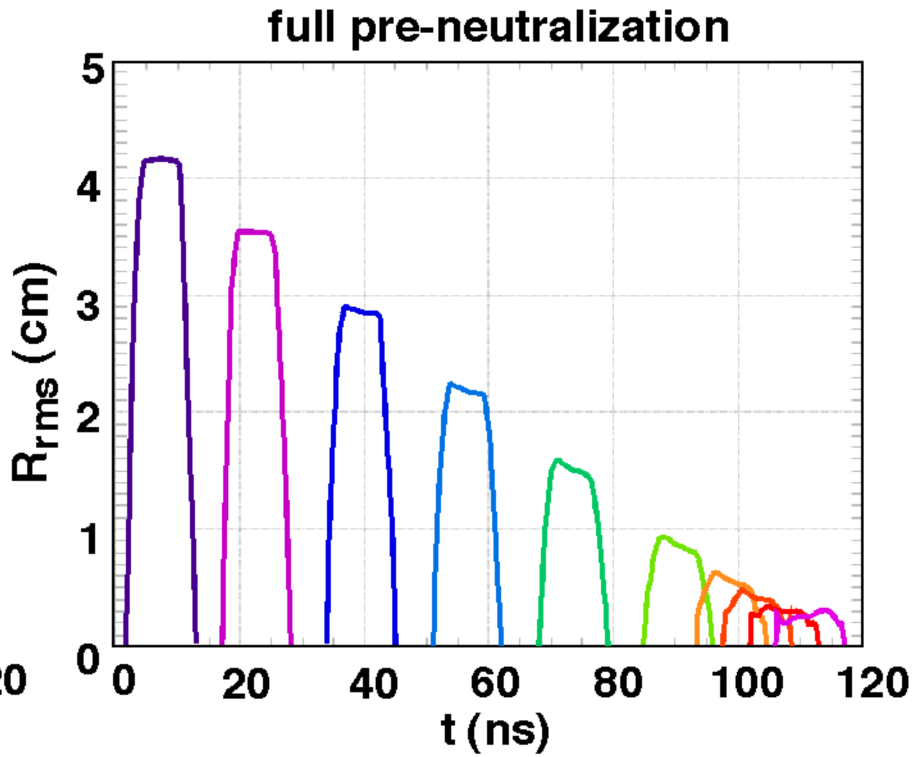
x- and *y*- envelopes for the Block E main pulse beams in the final focus system. The target is to the right.

Neutralization is required for small spot sizes

Results for standard Xe main pulse

- **time histories of rms radius at selected axial positions**
- **plasma is electrically connected to wall by images and emission**



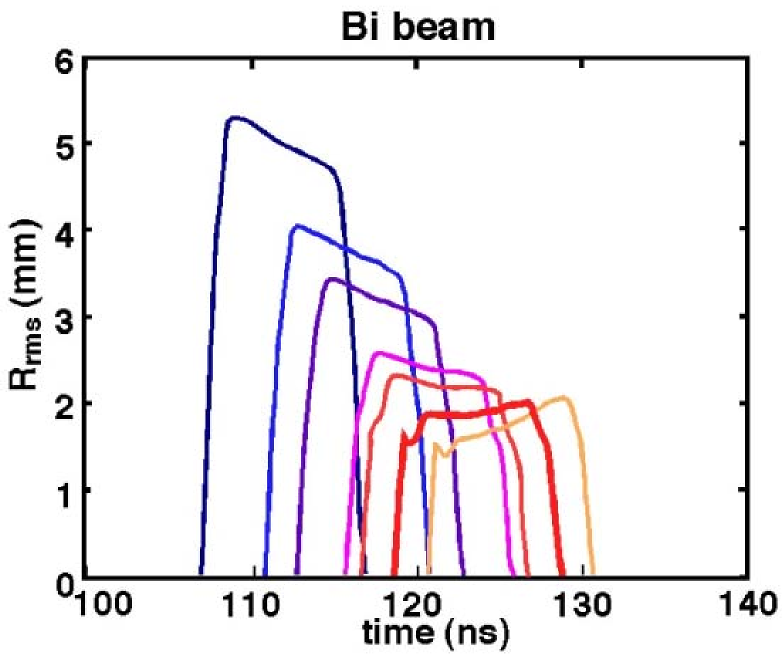


- **2.5 mm waist is close to value needed by distributed-radiator target**
- **Bi is easier to focus and meets spot requirement**

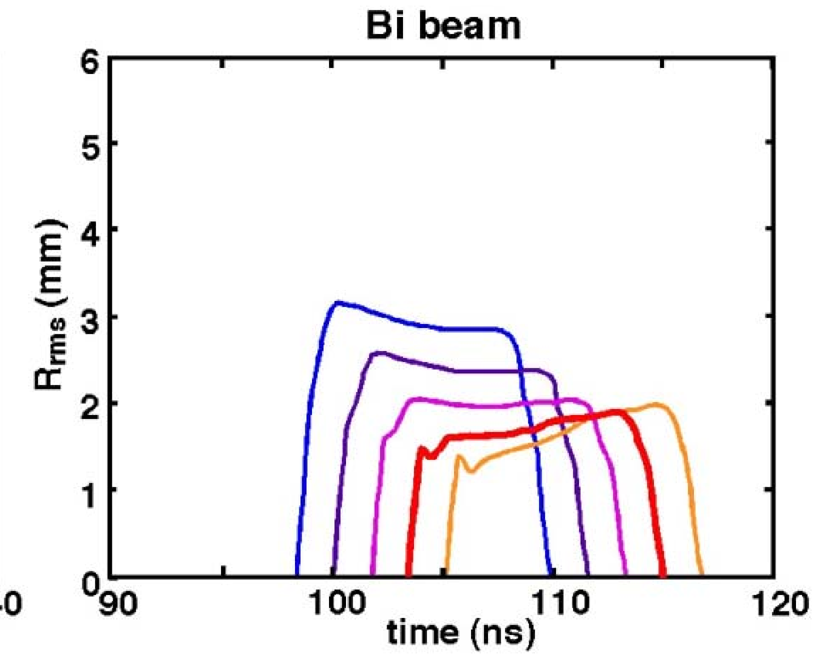
Spot size requirements can be met

Time histories of rms radius for standard Bi pulses

Foot pulse

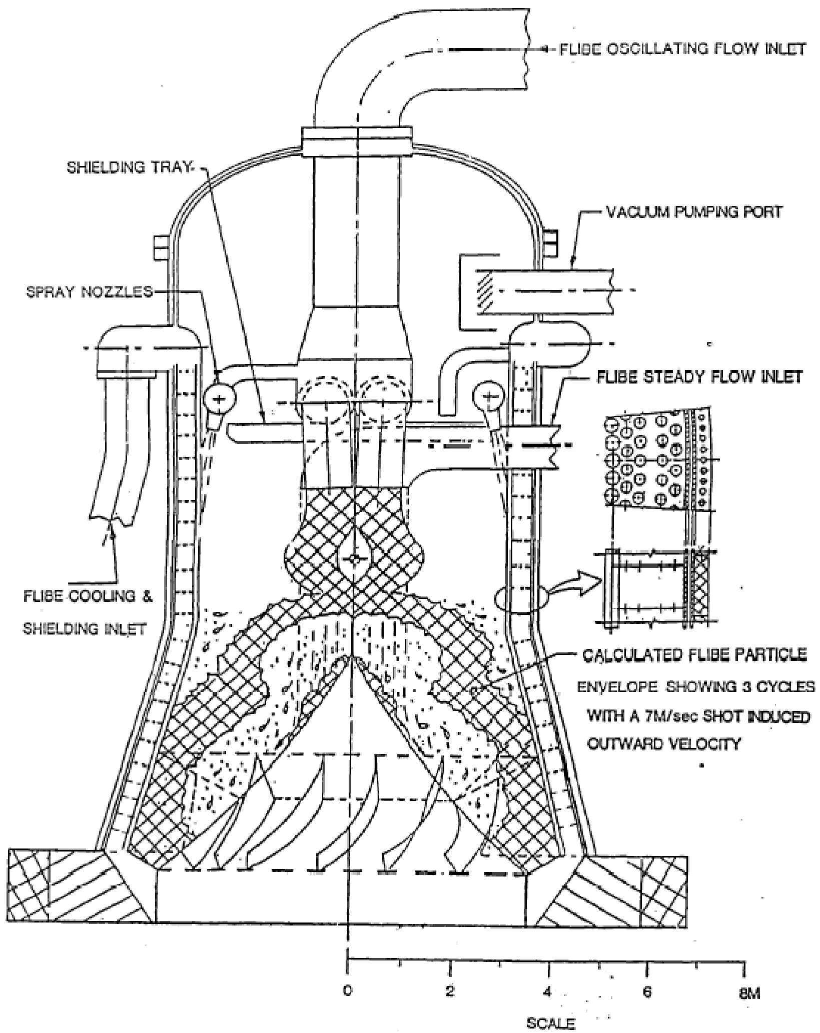


Main pulse



The 2.3 mm foot pulse spot size and 1.8 mm main pulse spot size requirements can be met.

Thick liquid walls allow major chamber structures to last many years

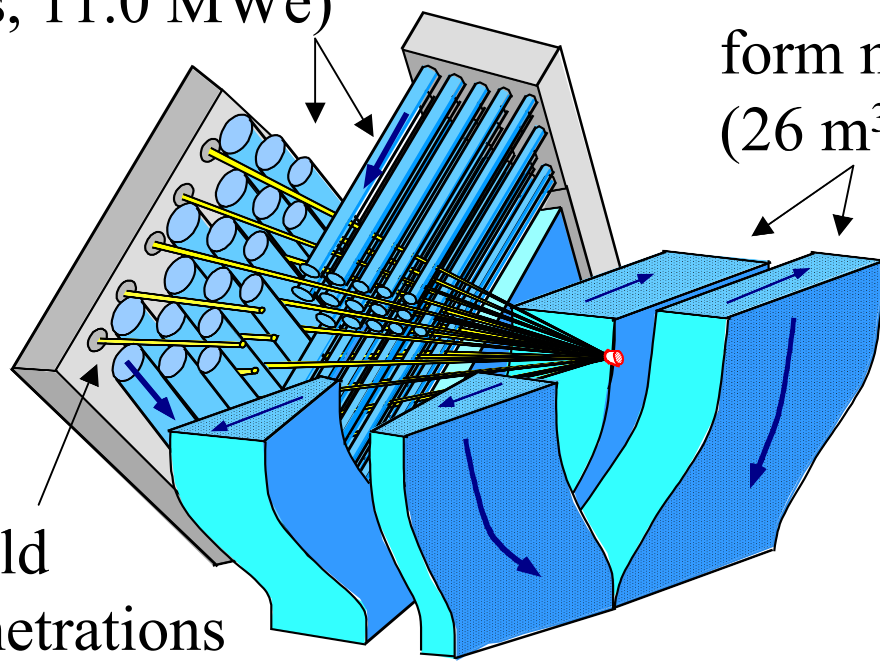


- A thick liquid pocket protects chamber structures from direct exposure to x-rays, ions, debris and neutrons.
- Liquid is molten salt – flinabe for point design
- Effective shielding thickness is 56 cm
- Oscillating jets dynamically clear droplets near target (clear path for next pulse).

The thick-liquid-wall chamber requires of 57 m^3/s total flow and 27 MWe for pumping power

Crossing jets
form beam ports
(20 m^3/s, 11.0 MWe)

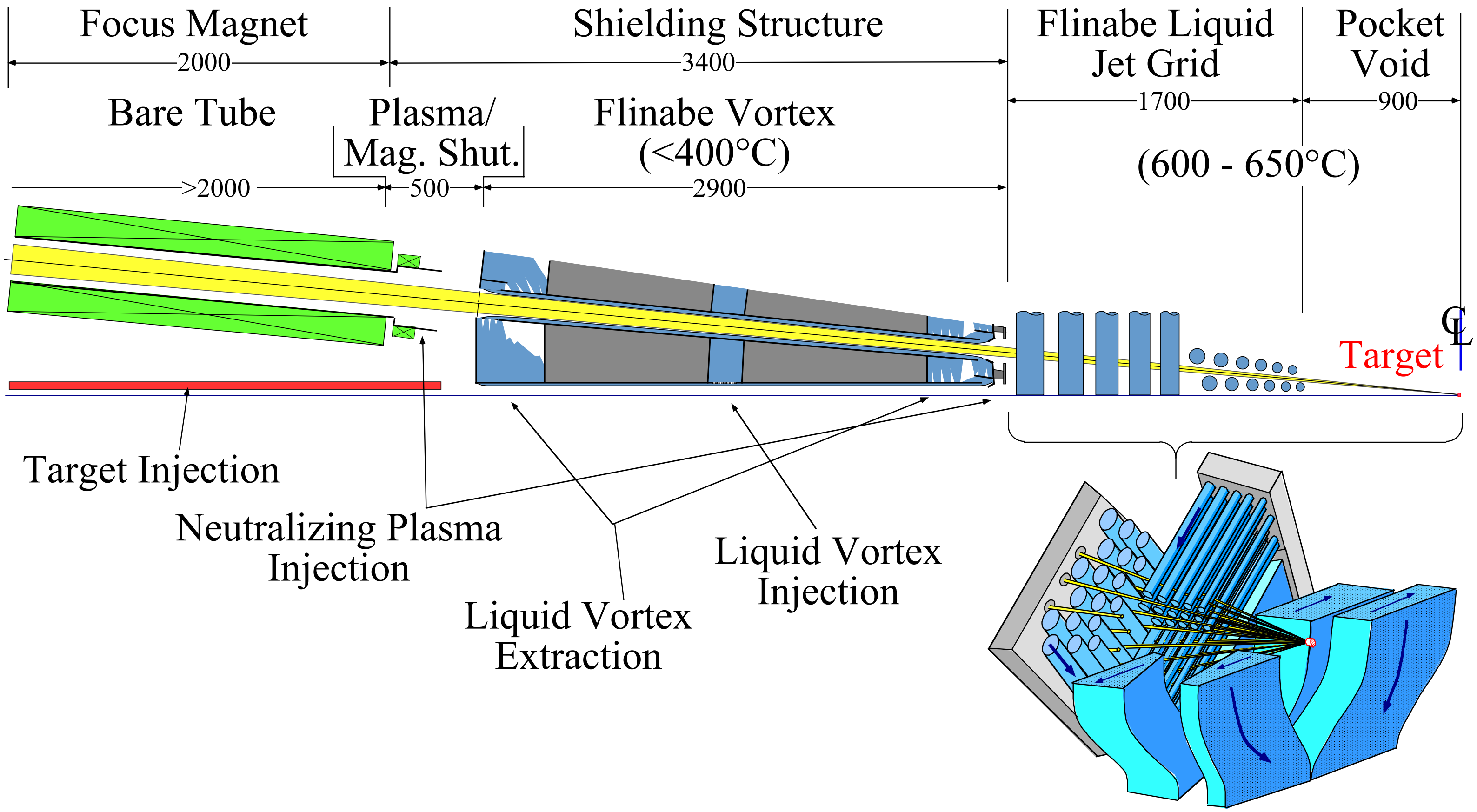
Oscillating jets
form main pocket
(26 m^3/s, 9.4 MWe)



Vortices shield
beamline penetrations
(5.3 m^3/s, 3.4 MWe)

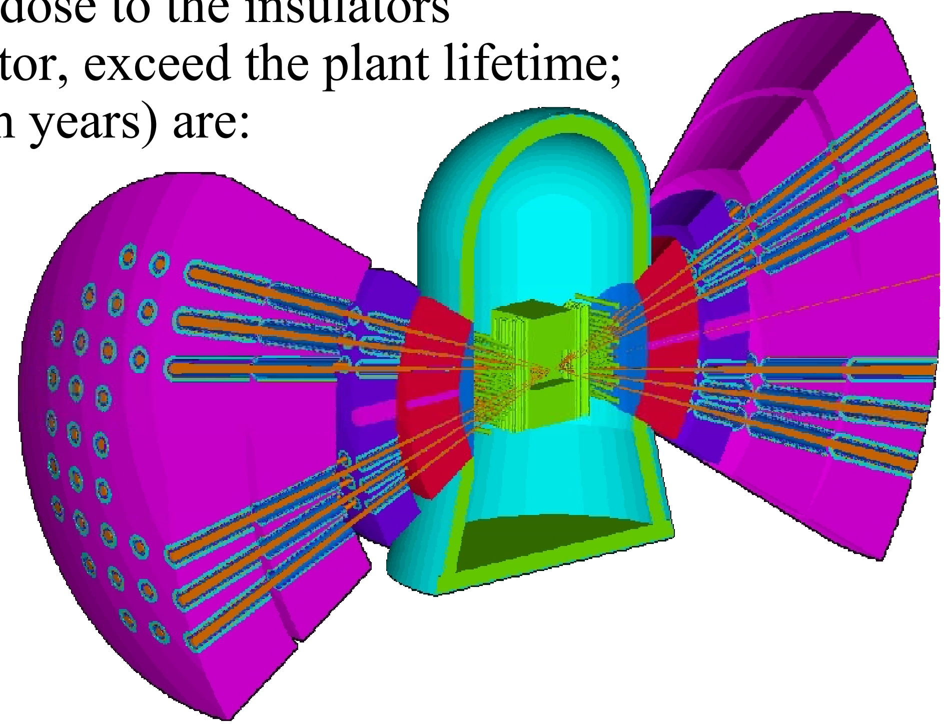
Other = 5.5 m^3/s, 3.4 MWe

The Robust Point Design (RPD) beam line



Schematic Liquid Jet Geometry

Recent magnet shielding & activation results are quite promising

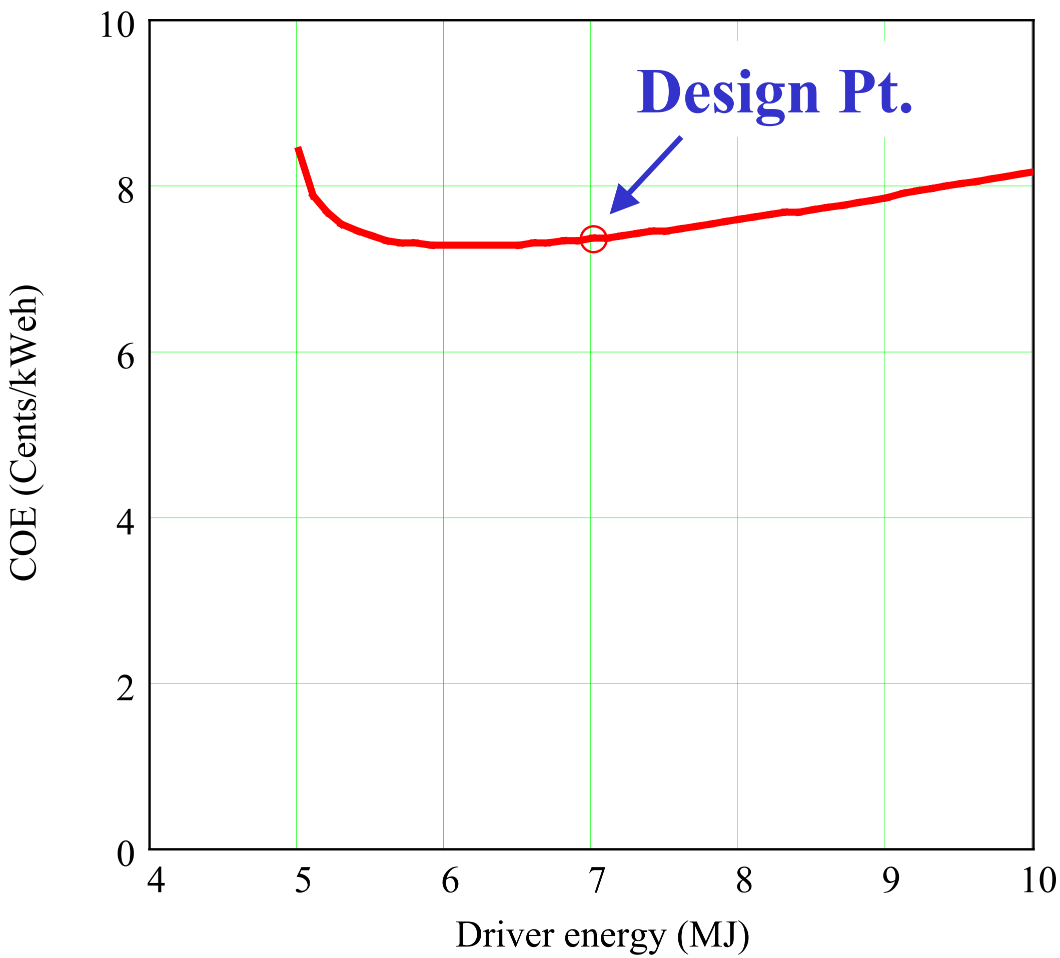


- Magnet lifetimes, which are limited by dose to the insulators and neutron fluence to the superconductor, exceed the plant lifetime; Insulator & superconductor lifetimes (in years) are:
  - Last magnet: 230/260
  - 2nd magnet: 410/1580
  - 3rd magnet: 100/610
- Waste disposal ratings are significantly reduced from previous work: 1.7, 0.5, 0.4 (^{94}Nb)
- Increasing liquid stand-off distance in vortices (from 1 → 5 mm) will reduce lifetimes by ~2x
- Optimizing shielding to increase neutron effectiveness (at cost of gamma-ray shielding effectiveness) should enable all magnets to qualify for disposal as low-level waste; adequate margin exists for magnet lifetime to exceed plant life.

Summary of power plant parameters

Driver energy, MJ	7.0
Target gain	57
Target yield, MJ	400
Pulse rep-rate, Hz	6.0
Fusion power, MW	2400
Thermal power, MWt	2832
Conversion efficiency, %	44
Gross electric power, MWe	1246
Auxiliary power, MWe	50
Pumping power, MWe	27
Driver efficiency, %	38
Driver power, MWe	110
Net electric power, MWe	1058
Driver cost, $B	2.78
Other plant costs, $B	2.27
Total power plant cost, $B	5.05
COE, ¢/kWeh	7.18

Cost of electricity at design point is near optimum for our robust assumptions



- ~ 1 GWe net
- COE = 7.2 ¢/kWeh
- 1% lower at E = 6 MJ, but rep-rate = 8 Hz

Opportunities for improvement in future designs

- **Target** - Focusing may be good enough to allow use of closer-coupled distributed radiator target designs that give high yield at lower driver energy (up to 2×).
- **Driver** - May be able to use lower mass ions (e.g., Xe^+, A = 131), which would reduce driver cost and COE.
- **Chamber Transport -** Use of dipole magnets to reduce emittance growth at entrance to plasma plug and thus reduce spot size.
- **Chamber** – Smaller beam array would reduce cross jet flow and pumping power. High temperature operation to improve thermal cycle efficiency.
- **FF Magnet Layout** - Improved final focus magnet configuration, e.g., clustering for more compact configuration, using race-track magnets with common structures, using modular cryostats, etc.
- **FF Magnet Shielding -** Optimization of FF magnet shielding to better balance neutron and gamma limits and to reduce waste disposal rating.

Summary

- We have developed a point design for a 1 GWe heavy ion fusion power plant that meets all known physics and technology constraints.
- A new target design, that allows beam entry from a larger angle (24°), has a predicted target gain is 57.
- The driver energy is 7 MJ and has a calculated efficiency of 38%.
- The thick-liquid-wall chamber operates at 6 Hz and requires 27 MWe for pumping power.
- The final focusing magnets are shielded by a combination of flowing molten salt jets and vortices, magnetic dipoles, and solid shielding material, resulting in lifetimes of 30 years or longer.
- The superconducting quadrupoles that constitute the final focusing magnets have very large apertures, stored energy and forces, but the fields required have been obtained in other particle accelerators.
- The final spot size, based on our analytic and numerical understanding of neutralized beam transport, meets the target requirements.

Related papers

Poster Session A

Shielding of the Final Focusing System in the HIF Point Design, J.F. Latkowski, W.R. Meier (LLNL)

X-Ray Ablation and Debris Venting for the Heavy-Ion Point Design, C. Debonnel, G. Fukuda, P. Peterson (Univ of California, Berkeley), Simon Yu (LBNL)

Poster Session B

An Integrated Mechanical Design Concept for the Final Focusing Region for the HIF Point Design, T. Brown, J. Chun, P. Heitzenroeder, J. Schmidt (PPPL)

Thick-Liquid Blanket Configuration and Response for the Heavy-Ion Point Design, S. Pemberton, R. Abbott, P.F. Peterson (Univ of California, Berkeley)

Diversion of Plasma Inside Beam Ports for Heavy Ion Inertial Confinement Fusion Chambers, D.V. Rose, D.R. Welch (MRC), C.L. Olson (SNL), S.S. Yu (LBNL)